

# Cost-Effective Strategies for the Sustained Control of Bait-Shy Vertebrate Pests in New Zealand

James G. Ross

Landsdowne Ventures Ltd, Christchurch, New Zealand

Katie B. Bicknell

Commerce Division, Lincoln University, New Zealand

**ABSTRACT:** The brushtail possum is a significant conservation pest and major vector of bovine tuberculosis in New Zealand. Previous control simulation studies have suggested that aerial control with bait containing sodium monofluoroacetate (1080) is the most cost-effective large-scale possum control strategy. However, there is a growing awareness that the survivors of 1080 control can develop 'bait shyness', and this can markedly alter the efficacy of ongoing 1080 control operations. Several alternative toxicants are registered for possum control but all are ground based, differ in their mode of action, and are more expensive than aerial 1080 control. A new possum control simulation model was developed to assist in identifying the most cost-effective control strategy that would achieve a sustained 80% population reduction, given bait-shy behaviour and immigration from adjacent non-controlled areas. The simulation results indicated that it is possible to achieve a sustained 80% population reduction (over a 10-year period) using a 1080-based control strategy, provided at least 90% of all 'susceptible' possums are killed in each control operation. In the event of an unsuccessful 1080 control operation (i.e., only a 60% kill), cyanide bait plus trapping, or brodifacoum bait provided the most cost-effective strategy of 'mopping up' 1080 bait-shy survivors. However, sufficient numbers of traps must accompany the cyanide bait to ensure that the majority of 1080 bait-shy possums are targeted. Sensitivity analysis indicated that the most important variable influencing the overall success of any control strategies was the rate of re-colonization following control. With the high rates of immigration that are sometimes observed in small forest reserves (i.e., <100 ha), it was not possible to sustain an 80% population reduction using any combination of toxicants. However, higher rates of immigration are probably exceptional and the rate used in these simulations is considered more typical, particularly for moderate-to-large forest stands where most possum control is conducted.

**KEY WORDS:** 1080, bait shyness, brodifacoum, brush-tailed possum, cost-effective control, cyanide, possum, sodium monofluoroacetate, *Trichosurus vulpecula*

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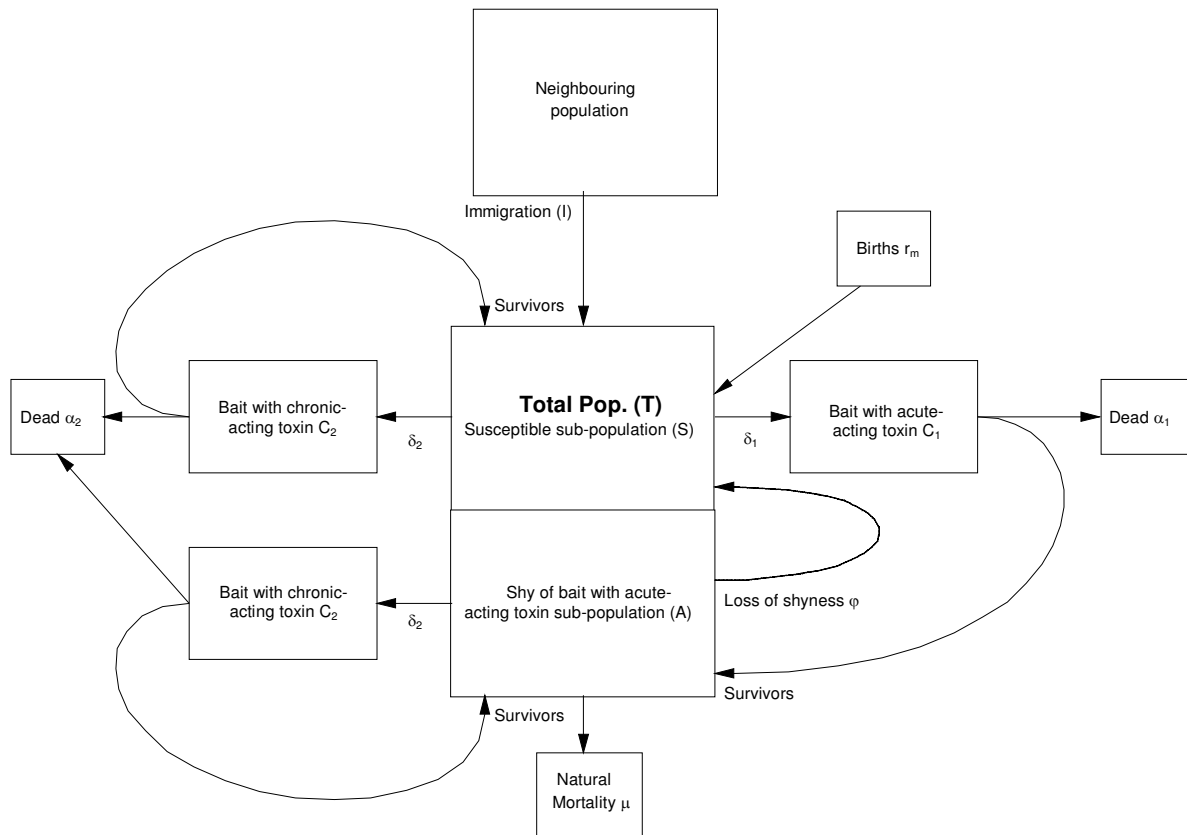
## INTRODUCTION

Since their introduction from Australia in 1858 (Pracy 1974), brushtail possums (*Trichosurus vulpecula*) have spread and now occupy more than 90% of New Zealand's land area, with an estimated population of 50 to 70 million (Clout and Ericksen 2000). Possums are a significant conservation pest, killing indigenous plants, suppressing regeneration through intensive browsing (Cowan 1991a, Payton 2000), and impacting on indigenous animals through predation, disturbance, and competition for resources (Innes 1994, Brown *et al.* 1996, Sadleir 2000). They are also considered the most important wildlife reservoir of bovine tuberculosis (*Mycobacterium bovis*, Tb), which they spread to cattle and farmed deer (Coleman and Caley 2000). Increased levels of Tb infection in cattle and deer herds could restrict our NZ\$5 billion export market for beef, venison, and dairy products. It has been estimated that such restrictions on access for meat and dairy products could cost New Zealand up to NZ\$500 million annually (Coleman and Livingstone 2000).

Consequently, central and local government agencies spend millions of dollars (NZ) every year on possum management activities. As an example of the magnitude of these expenditures, it has been estimated that approximately NZ\$80 million was spent on possum control throughout New Zealand in the 2004/05 financial

year (NPCA 2006), with a further NZ\$12 million spent on research activities (NSSC 2004). Unfortunately, this level of funding remains insufficient to control possums in all Department of Conservation (DoC) and Animal Health Board Inc. (AHB) priority areas (PCE 1994), and difficult decisions must be made regarding the location of each year's control operations. Regardless of the criteria used to determine which areas receive possum control, field managers must then make decisions concerning the most appropriate control technique. As there is only a limited amount of money available for pest control, it is important that the most cost-effective techniques are used (Cullen and Bicknell 2000).

Previous research investigating cost-effective control of possums has favored the use of aerially-delivered sodium monofluoroacetate (1080) bait (Barlow 1991a). This technique can significantly reduce high-density possum populations over areas as large as 20,000 ha (Morgan and Hickling 2000); however, an over-reliance on one toxicant for sustained control is considered unwise (Eason *et al.* 1994). One of the main reasons is that regularly-controlled populations can develop behavioral mechanisms to avoid bait with acute-acting toxins (Ross *et al.* 2000, O'Connor and Matthews 1996). Field and pen trials have demonstrated that the majority of 1080-control survivors will develop 'bait shyness' following sub-lethal poisoning (Ross *et al.* 1997). This bait shyness



**Figure 1. Flowchart for a computer simulation of possum population responses to a toxic baiting strategy employing acute and chronic-acting toxins. See Table 1 for an explanation of the variables.**

**Table 1. Variable definitions and values used in a computer simulation of possum population responses to a toxic baiting strategy employing acute and chronic-acting toxins.**

	Definition	Value
S	Density of possums susceptible to poisoning	per ha
A	Sub-population of possums shy of bait with an acute-acting toxin	per ha
I	Number of immigrants from neighboring population	per ha
T	Total possum population in controlled habitat	per ha
L	Number of possums losing acute-acting toxin bait shyness	per ha
C <sub>1</sub>	Acute-acting toxin control activity	0 - 1
C <sub>2</sub>	Chronic-acting toxin control activity	0 - 1
M	Maximum migration rate (possums/ha/yr)	1.2
r <sub>m</sub>	Maximum rate of intrinsic increase for controlled possums/year	30%
K	Carrying capacity for controlled possums/ha	10
μ	Natural mortality rate/year for possum in sub-population (A)	10%
θ	Shape parameter for possum population growth curve	3
δ <sub>1</sub>	Percentage of population exposed to bait with an acute-acting toxin	100%
δ <sub>2</sub>	Percentage of population exposed to bait with a chronic-acting toxin	100%
α <sub>1</sub>	Percentage of population killed by bait with an acute-acting toxin	79-99%
α <sub>2</sub>	Percentage of population killed by bait with a chronic-acting toxin	75%
φ	Acute-acting toxin bait shyness period decay/year	17%
C	Cost of control operation	\$/ha
t	Number of years since start of simulation	1-10
l	Discount rate	10%
a	Size of the control area	5,000 ha

is long-lived (Morgan *et al.* 1996a) and can render 1080 follow-up maintenance control ineffective (Hickling 1994). Accordingly, possum control strategies need to incorporate other control techniques, such as ground control with traps and alternative chronic-acting toxins (5 other possum toxins are registered in New Zealand). This paper extends previous possum modeling work (e.g., Barlow 1991a, Hickling 1994) by developing a new possum bioeconomic model that incorporates 1080 bait shyness and the latest methods of possum control, including macro-encapsulated cyanide and anticoagulants.

## METHODS

This bioeconomic model was originally developed in the late 1990s (see Ross 1999). It has recently been updated using field data obtained from a research project conducted by Epro Ltd in a 5,214-ha indigenous forest site near Hatepe in the central North Island, New Zealand (Epro 2003, Ross 2004).

## Equations

The basic model (Figure 1) was constructed as a Microsoft® Excel 2002 spreadsheet and uses the following equations for changes in density of the total population (T), which is made up of a susceptible sub-population (S) and a shy of acute-acting toxin bait sub-population (A):

Susceptible sub-population:

$$\frac{dS}{dt} = (S + I + (Tr_m(1 - (T/K)^0)) + L) * (1 - C_1\delta_1 - C_2\alpha_2)$$

[Equation 1]

Shy of bait with an acute-acting toxin sub-population:

$$\frac{dA}{dt} = A(1 - \mu - \phi) + C_1(1 - \alpha_1) * (S + I + (Tr_m(1 - (T/K)^0)) + L) - C_2\alpha_2A(1 - \mu - \phi)$$

[Equation 2]

Total population:

$$T = (S + A)$$

[Equation 3]

The modeling simulation was set up to estimate the total possum population (T) at 12-month intervals. The values in the Table 1 are, therefore, per annum estimates derived from various captive and field research studies.

## Model Parameters

### Biological Growth of the Possum Population (Births)

The biological growth of the possum population was modeled using a rightwards-peaked  $\theta$ -logistic equation (Gilpin *et al.* 1976). Ecological studies investigating population dynamics suggest that brushtail possum populations are regulated by density-dependent mortality, intensifying near carrying capacity (Barlow 1991a). This implies that the possum population growth curves are asymmetrically rightward-peaked (Barlow and Clout 1983). The value for  $\theta$  was obtained from an empirical study monitoring population recovery following a major poisoning operation. The results of this study suggest that a  $\theta$  value of 3 most accurately modeled population

recovery in indigenous forest habitat (Hickling and Pekelharing 1989).

### Maximum Intrinsic Growth Rate/Year

Possums have a significant birth pulse in autumn and sometimes a smaller one in spring, which is referred to as double breeding (Batcheler and Cowan 1988). Empirical estimations of  $r_m$  vary from a low of 20% (Hickling and Pekelharing 1989) to 59% (Keber 1985). Most of the values used in previous possum modeling simulations have been in the range of 20-30%, with variation dependent on habitat. In this modeling exercise, we used a value of 30%, which should be appropriate for indigenous forest habitat.

### Carrying Capacity

Estimated values for carrying capacity (K) vary from less than one possum/ha in unfavorable scrubby farmland to over 25 possums/ha in blocks of highly favorable habitat (Clout and Efford 1984, Cowan 1991b). In this model, the control population was assumed to be located in indigenous forest habitat in the central North Island. Population studies suggest that this type of habitat often supports medium to high-density populations (Coleman *et al.* 1980, Green and Coleman 1986, Brockie *et al.* 1987) for which previous modeling simulations have used an upper value of 10 possums/ha.

### Possum Movement

The movement of small mammals between adjacent parcels of habitat has been widely investigated by population ecologists. It is hypothesized that dispersal is governed by within-group competition for resources, such as den space, and between-group exchange of individuals through migration (Hestbeck 1982). This is referred to as a "social-fence", which "opens" and "closes" depending on the population densities in the parcels of habitat.

A mathematical model of the social-fence, which has been adapted and applied to models investigating optimal control of beavers (Huffaker *et al.* 1992) and the spread of bovine Tb by the brushtail possum (Barlow 1993), is as follows:

$$\frac{dI}{dt} = M \left( 1 - \frac{T}{K} \right)$$

[Equation 4]

This equation assumes that when the density in the controlled area is low, possums will migrate from the relatively densely populated non-control (neighboring) area up to a maximum migration rate (M). The equation also assumes that dispersing possums are of breeding age and equal sex ratio. Both assumptions are broadly consistent with the field data, which has demonstrated that control areas are rapidly re-colonized by a high proportion of adult possums (Keber 1985) of both sexes (Clout and Efford 1984, Green 1984).

### Maximum Immigration Rate from the Neighboring Population

An estimate for the maximum rate of immigration (I) back into the control area was derived from a number of field studies. In a total removal experiment, possums

began re-colonizing a 24-ha pine plantation (Kinleith Forest, North Island) within one month of the control operation. After one year, the density was 1.6 possums/ha, which was 55% of the original population density (Clout and Efford 1984). In another total removal experiment, a 12-ha area in the Orongorongo Valley was rapidly re-colonized by 12 possums after one year (Barlow 1993). In an experiment in the South Island, possums were removed from a 125-ha block of indigenous forest in Westland. The pre-control density was 10.7 possums/ha, and 3 years later this population was back to 26% of the pre-control density (Green and Coleman 1984). In a more recent study, 255 possums (90% kill) were removed from 23 ha of swamp and willow habitat in the Hawkes Bay (North Island). Five years later, the population had recovered to a density of 5.9 possums/ha (Cowan *et al.* 1997). These studies suggest that the upper limit for possum immigration, back into a control area, is approximately 1.2 possums/ha/yr.

### Development of Bait Shyness

“Shyness” is a generic term indicating avoidance of a bait or poison. There are actually several mechanisms that can reduce an animal’s tendency to consume a lethal dose of toxic bait (O’Connor and Matthews 1996, Ross *et al.* 2000). Previous research suggests the most likely mechanism used by possums to avoid toxic bait is a conditioned food aversion (Hickling 1994). This is a learned behaviour that is generally induced by a sub-lethal dose of an acute-acting toxin. A definition of an acute-acting toxin is one that brings about death, after the administration of a lethal dose, in 24 hours or less (Buckle 1994).

### Acute-Acting Toxin Bait Shyness

Pen trials have demonstrated that the majority (>60%) of possums will develop an aversion to similar bait (hereafter referred to as bait shyness) following a sub-lethal dose of 1080, cyanide, or cholecalciferol (O’Connor and Matthews 1995, 1996; Ross *et al.* 1997; O’Connor *et al.* 1998). Such pen trials have also demonstrated that bait shyness can be long lasting (>24 months) and has the potential to dramatically effect the efficacy of future control operations (Morgan *et al.* 1996a). The most striking field example of this comes from Mapara Forest (North Island), where the estimated annual 1080-aerial possum kill declined from 79% to 32%, and then to 0% over a period of 3 years (Warburton and Cullen 1993). In this modeling exercise, bait shyness was included as a model parameter for simulations using 1080 and cholecalciferol. This means that most of the control survivors would avoid similar baits in future encounters; however, the number of bait-shy possums decreases in the absence of further control (see below). For the control work using cyanide, the number of survivors developing bait shyness was reduced to zero, as contractors also use dogs and leg-hold traps to ‘mop up’ any bait-shy possums.

### Acute-Acting Toxin Bait Shyness Period Decay

An estimate of the rate of acute bait shyness degradation ( $\phi$ ) was derived from two long-term trials

with captive possums. Both captive studies ran for 24 months and produced similar results. In the first captive trial, 71% of sub-lethally dosed (1080) possums remained bait shy after 3 months, 63% after 12 months, and 57% after 24 months (Morgan and Milne 1997). In the second captive trial, 80% of sub-lethally dosed (cyanide) possums were bait shy 1 month later and 60% after 24 months (C. O’Conner, Landcare Research Ltd, pers. commun. 1998). These data suggest that the number of bait-shy possums will decrease by approximately 40% over 2 years, with most of the reduction occurring in the first 12 months.

The degradation of bait shyness was modeled using an exponential decay equation (Equation 5). Using this type of equation, the maximum rate of bait shyness degradation occurs in the first year and then slows over the remaining 9 years. Sensitivity analysis indicated that a value of 17% most closely fitted the 5 data points given above. Similar versions of this equation have been used by other researchers to model the rate of degradation of pesticide residue in soil (Feder and Regev 1975).

$$\frac{dL}{dt} = (A\phi) \quad [\text{Equation 5}]$$

### Chronic-Acting Toxin Bait Shyness

Chronic-acting toxins are generally referred to as the anticoagulants. With these compounds, poisoning symptoms are delayed (e.g., 4-10 days in rodents), and the target animal fails to associate poisoning symptoms with the anticoagulant and bait shyness does not develop (Buckle 1994). This hypothesis is further supported by a recent captive possum trial where researchers were unable to detect any brodifacoum bait shyness following sub-lethal doses of 0.05 and 0.1 mg/kg body weight (O’Connor *et al.* 1998). Field studies with possums also indicate that anticoagulants will kill the majority (>70%) of bait-shy survivors following unsuccessful control with bait containing acute-acting toxins (Henderson *et al.* 1997).

### Mean Percentage Kill Estimates for the Different Toxins

Mean percentage kill estimates for 1080, cyanide, and cholecalciferol were derived from the Epro Ltd research project. This study indicated that 1080 had the highest control efficacy (Table 2), followed by cyanide with trapping and cholecalciferol.

**Table 2. Mean percentage kills ( $\pm$  SEM) for the five different control techniques.**

Control Technique	Kill (%)	Replicates
1080 aerial	99.05 $\pm$ 1.36	4
1080 bait stations	93.66 $\pm$ 2.93	4
cyanide & trapping	88.04 $\pm$ 5.12	4
cholecalciferol	79.29 $\pm$ 7.96	4
brodifacoum	75.25 $\pm$ 5.85	4

Brodifacoum was not used in the study site due to concerns regarding the poisoning risk for non-target species (Eason *et al.* 2002) and the higher per/ha cost when used in areas with a moderate-to-high high possum

density. Therefore, a mean value for brodifacoum control efficacy was estimated from 4 research field trials where brodifacoum was applied immediately following unsuccessful control with an acute-acting toxin. As detailed above, bait shyness is not a significant problem when using a chronic-acting toxin, and control efficacy for brodifacoum does not decrease during ongoing maintenance control operations (Henderson *et al.* 1997).

The other two registered toxins for possum control are pindone and phosphorous. Pindone was not included, as studies have shown that it has poor field efficacy, and phosphorous is considered to be inhumane (Eason 1996). Other toxins are currently being developed (e.g., zinc phosphide; Ross and Henderson 2006); however, none have yet obtained full registered status.

### Mean Operational Cost of Control for the Different Toxins

Mean cost estimates for 1080, cyanide, and cholecalciferol were also derived from the Epro Ltd research project (Table 3). These data indicate that aerial control with 1080 was substantially cheaper than the ground-based control techniques. There was little difference in the mean cost of the ground-based control techniques; however, there was considerable cost variation for control operations using cyanide and trapping. Cost estimates for these techniques ranged from a low of NZ\$19.57 to a high of \$70.53/ha. This was due to the fact that additional control work was required in some blocks to meet the control targets. The cost of control for the aerial and ground-laid 1080 remained consistent, because there was no additional control or re-monitoring required. The cost of cholecalciferol was fixed, because the contract was for service only with no requirement for additional control if targets were not met (C. Speedy, Epro Ltd, pers. commun., 2004). The mean cost of brodifacoum control was estimated from 5 ground-control operations conducted by DoC (Ross 1999).

**Table 3. Cost NZ\$/ha for the five different possum control techniques.**

Control Technique	Mean Cost	Low	High	Replicates
1080 aerial	\$20.25	-	-	4
cholecalciferol	\$36.46	-	-	4
1080 bait stations	\$43.45	-	-	4
cyanide & trapping	\$43.82	\$19.57	\$70.53	4
brodifacoum	\$57.00	-	-	5

### Additional Regulatory Costs

In addition to the direct costs of control, there is also a requirement to obtain approval from the Ministry of Health and resource consent from the local Regional Council for aerial control operations. Often these costs are overlooked, but they need to be factored in for a valid comparison of aerial and ground-based possum control. Estimates of these costs were obtained from the West Coast Regional Council. In addition to this, some possum control activity takes place on DoC land. In these areas, an Assessment of Environmental Effects (AEE) application is also required.

Certainly, there are more regulatory costs for aerial control; however, the per-hectare impact of these additional consent costs is lessened by the fact that aerial control usually takes place over larger operational areas. Accordingly, the calculated cost/hectare is not significantly different from ground-based techniques (Table 4).

### Discount Rate Used in the Simulations

All of the possum control simulations used the mean cost values from Table 3 and incorporated the appropriate regulatory costs from Table 4. These figures were then discounted to determine the net present value of the different control strategies, using a 10% discount rate. This value has been typically used in New Zealand for analysis of government-funded projects (Forbes 1984) and has also been used in previous possum control modeling simulations (Barlow 1991a, Warburton and Cullen 1993).

**Table 4. Costs (NZ\$/ha) of obtaining Ministry of Health approval, resource consent and DoC approval for ground and aerial-control operations.**

Ground Control	Cost	Average Consent Cost \$/ha <sup>1</sup>
DoC (AEE)	\$1,200	\$0.15
Ministry of Health application	\$500	\$0.06
<b>TOTAL</b>	<b>\$1,700</b>	<b>\$0.21</b>
Aerial Control	Cost	Average Consent Cost \$/ha <sup>2</sup>
DoC (AEE)	\$2,500	\$0.22
Ministry of Health application	\$500	\$0.04
Resource consent application	\$7,873	\$0.70
Pre-consultation management	\$3,000	\$0.27
Council monitoring	\$1,200	\$0.11
<b>TOTAL</b>	<b>\$15,073</b>	<b>\$1.34</b>

<sup>1</sup> average ground control area 8,206 ha (range 546 - 25,474)

<sup>2</sup> average aerial control area 11,194 ha (range 4,288 - 29,954)

### Goal of Modeling Simulations

Most possum control operations aim for population reductions that result in a residual trap catch index (RTCI) of less than 2% (i.e., <2 possums per 100 trap-nights) during post-control monitoring (NPCA 2002). Previous modeling suggests that a sustained 80% population reduction should ensure that the possum population is not allowed to recover after the initial "knock-down" control operation (Ross 1999). Whilst the value of 80% may seem low, the population density is continually measured throughout the year (allowing for natural recruitment and immigration), and not just measured immediately following the control operation. This means that the average possum population density will not exceed 20% of the pre-control population density throughout the time frame of the simulation. This is well below the predicted threshold for disease transmission (40% of carrying capacity for possums; Barlow 1991b), and it is also generally accepted that a sustained 80% reduction should provide significant protection for vulnerable indigenous flora and fauna (Hickling 1994).

Previous modeling simulations (see Ross 1999) indicate that the two key variables influencing the ability

of a control strategy to maintain the population below the target threshold were the percentage kill in the initial control operation and the rate of immigration following control. Accordingly, we ran additional simulations where the percentage kill of the initial control operation was reduced to 60% and further simulations where the maximum rate of immigration was doubled. Sometimes control operations fail, and a value of 60% is not uncommon where bait may be of low quality and/or has an inappropriate toxin concentration (Morgan *et al.* 1986, Henderson and Morris 1996). Also, we used a mean value for the maximum rate of immigration back into the control area. Complementary research suggests that rates of immigration into small reserves (<100 ha) can be substantially higher (Thomas *et al.* 1995) than those experienced in larger control areas (>10,000 ha) (Hickling and Pechelaring 1989).

### Time Frame of the Simulation

Previous possum models have run over a time frame of 5 (Barlow 1993), 3 (Roberts 1996), 8 (Barlow 1991a), 12 (Hickling 1995), and 28 years (Pfeiffer 1994). Hickling (1995), who was the first to investigate the implications of behavioral resistance on the efficacy of 1080 control operations, argued that a 10-year period is the minimum required to gauge the effectiveness of multiple-poisoning campaigns on a possum population. Accordingly, we ran all our model simulations over a 10-year period.

## RESULTS

### Sustained 80% Population Reduction

The most cost-effective strategy for achieving a sustained 80% population reduction was aerial 1080 with an accumulated discounted cost of NZ\$59/ha over the 10-year period (Figure 2). 1080 pellets in bait stations was the next cheapest option; however, the cost was very similar to cyanide and trapping (Table 5). Cholecalciferol could not achieve the sustained 80% reduction primarily due to lower control efficacy, which resulted in increasing numbers of bait-shy possums in the population. Brodifacoum was able to achieve the population reduction target even with the lowest control efficacy, because there was no buildup of bait-shy possums; however, control using brodifacoum was the most expensive strategy.

### Sustained 80% Population Reduction with Poor Initial Control Operation

The influence of an initial unsuccessful 1080 operation meant it was not possible to achieve the sustained 80% population reduction solely using 1080.

The most cost-effective strategy was immediate “one-off” control, using either cyanide plus trapping, or brodifacoum to target the bait-shy survivors (Figure 3). This was then followed by 1080 control every second year, which kept the population in check by killing the bulk of the new immigrants and recruits. The inclusion of an extra control operation to target the bait-shy possums effectively doubled the accumulated cost of control (Table 6) and highlights the cost-effectiveness of control solely using aerial-delivered 1080.

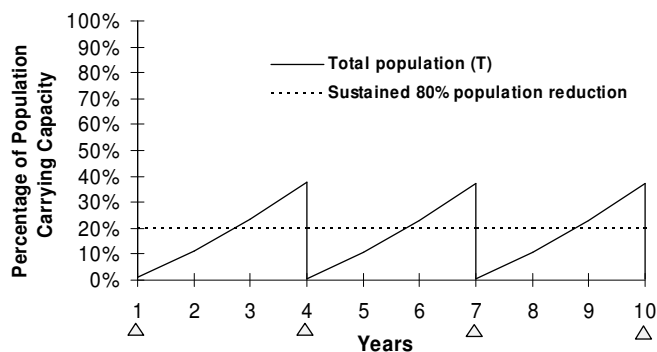


Figure 2. Possum population density following aerial control with 1080 ( $\Delta$ ) every third year.

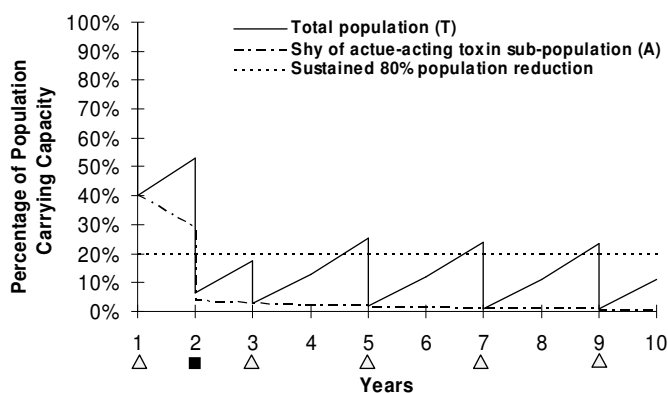


Figure 3. Possum population density following aerial control with 1080 ( $\Delta$ ), and cyanide and trapping ( $\blacksquare$ ) in Year 2.

### Sustained 80% Population Reduction with Higher Immigration

With the higher maximum rate of immigration, 9 years of aerial 1080 control was required to achieve the sustained aware that an initial kill of only 80% will have 80% reduction (Figure 4). This target could also be achieved using a combination of 1080 with either cyanide plus trapping, or brodifacoum; however, these strategies

Table 5. Accumulated discounted cost of the five different possum control strategies attempting to achieve a sustained 80% kill.

Control Option	Strategy	Cost NZ\$/ha	Sustained Population Reduction
1080 aerial – 99% kill	control every 3 yrs	\$59	80% – Pass
1080 bait stations – 94% kill	control every 2 yrs	\$155	81% – Pass
cyanide and trapping – 88% kill	control every 2 yrs	\$156	80% – Pass
cholecalciferol – 80% kill	10 years of control	\$248	75% – Fail
brodifacoum – 75% kill	8 years of control	\$333	81% – Pass

**Table 6. Accumulated discounted cost of possum control strategies, attempting to achieve a sustained 80% kill, using 1080, cyanide, and trapping and brodifacoum following an initial unsuccessful 1080 operation.**

Strategy	Cost NZ\$/ha	Sustained Population Reduction
Initial 1080 – 60% kill, then 1 year cyanide and trapping – 88% kill plus every 2 years 1080 – 99% kill	\$116	81% – Pass
Initial 1080 – 60% kill, then 1 year brodifacoum – 75% kill plus every 2 years 1080 – 99% kill	\$128	80% – Pass



**Figure 4. Possum population density following annual aerial control with 1080 ( $\Delta$ ).**

**Table 7. Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080, cyanide and trapping and brodifacoum with increased possum immigration.**

Strategy	Cost NZ\$/ha	Sustained population reduction
9 years 1080 – 99% kill	\$137	82% – Pass
8 years 1080 – 99% kill then 1 year cyanide and trapping	\$147	82% – Pass
8 years 1080 – 99% kill then 1 year brodifacoum	\$154	81% – Pass

were marginally more expensive (Table 7). It was not possible to achieve the population reduction using 1080 in bait stations or any other combination of toxins.

## DISCUSSION

What the modeling simulations clearly highlight is the importance of control efficacy. Control methods with low efficacy (<90% kill) required significantly more effort to maintain the population below the target density. Accordingly, while cost of cholecalciferol control was cheaper than 1080 in bait stations, field managers need to be aware that an initial kill of only 80% will have implications further down the track. Not only will additional control be required to meet target objectives, but lower initial efficacy creates greater numbers of bait-shy survivors. These bait-shy survivors become difficult to control using bait with an acute-acting toxin, and managers then have to switch to a more expensive control

method (e.g. cyanide plus trapping, or brodifacoum) to deal with this problem. Previous possum control modeling suggests that the most cost-effective way to control possums is to hit them hard in the initial control operation (Ross 1999). Aerially-delivered 1080 bait killed 99% of possums in the study area. This meant that control only every third year was required to meet the target objectives, as the population took longer to recover between the control operations.

The most cost-effective control strategy was aerially-delivered 1080 bait. Aerial 1080 had a discounted cost of NZ\$59 per hectare, and this was less than half the cost of the other ground-based methods. As detailed above, this was partially the result of high control efficacy, but it also reflects the lower costs of aerial delivery. This result is not terribly surprising, as considerable research effort has gone into perfecting aerial delivery (e.g., Global Positioning Systems technology) and developing “best practice” for this method in New Zealand (Morgan *et al.* 1996b). As a result, the cost of aerially-delivered 1080 has not significantly changed over the past decade (Warburton and Cullen 1993), and even with the inclusion of additional regulatory costs, it is still considerably cheaper than all ground-based control strategies. If the use of 1080 bait (aerial or ground-based) is not feasible on political grounds, then cyanide and leg-hold trapping is the next most cost-effective control strategy. However, there was considerable variation in the reported cost of this control option (Table 3). Part of the reason for the cost variability was that some contractors used cyanide exclusively, and then resorted to trapping only after failure to meet performance goals (C. Speedy, Epro Ltd, pers. commun. 2005). Accordingly, the additional costs of trapping, and subsequent re-monitoring, inflated some of the cyanide and trapping cost estimates.

The results reported above also highlight how important the percentage kill achieved in the initial control operation is. Whilst the model indicated that it was still possible to achieve a sustained 80% population reduction, with only a 60% kill in the first control operation, the inclusion of additional operations (using cyanide plus trapping, or brodifacoum) to target bait-shy survivors significantly increased the total cost of control. For example, an initial unsuccessful aerial 1080 operation increased costs by at least NZ\$57/ha (a 96% cost increase). This highlights how important it is for field managers to ensure all bait is probably prepared and delivered, particularly for the initial control operation when the population density is at its highest level.

An important consideration is that whilst the modeling indicated that cyanide plus trapping is slightly more cost-effective than brodifacoum for ‘mopping up’ bait-shy possums, the only field-proven toxin that will kill bait-shy possums is brodifacoum (Morgan and Ross 2001). In our modeling simulations, we turned off the shyness parameter for cyanide plus trapping, as the traps should target any bait-shy survivors. As detailed above, it seems that contractors vary their level of control effort, and this is of concern. For example, contractors may reduce their costs by decreasing the numbers of trap lines and primarily rely on cyanide bait. Wary, bait-shy possums

from previous control could avoid these baits (O'Connor and Matthews 1996), and the ultimate success control of cyanide plus trapping, as a maintenance control option rests on the ability of this technique to target bait-shy survivors. Alternatively, field managers could use brodifacoum in bait stations. As detailed above, the use of this compound has been restricted due to concerns regarding the poisoning risk for non-target species (Eason *et al.* 2002). Our simulations indicate that brodifacoum only needs to be used following an unsuccessful control operation, and this should ensure long-lived brodifacoum residues do not accumulate in the environment.

Finally, these simulations also highlight the importance of the rate of immigration back into control areas. With a higher maximum rate of immigration, it was no longer possible to achieve a sustained 80% population reduction using any toxin with less than 99% efficacy. The maximum rate of immigration used in the base model (1.2 possums/ha/yr) was derived from field studies investigating population recovery in a variety of habitats. Some of these study sites were small (12-24 ha) and surrounded by very favorable possum habitat. This suggests that higher rates of immigration are probably exceptional and a maximum rate of 1.2 possums/ha/yr is more typical, particularly in moderate-large forest stands (Hickling and Pekelharing 1989).

Whilst these field data indicate that rates of higher immigration are unlikely, they do highlight a need for field managers to conduct pre-control monitoring to accurately gauge rates of population recovery. Currently, most population monitoring is only conducted post-control, to assess whether the contractor has achieved a target density and/or that control effort is uniform throughout the control site (K. Barber, West Coast Regional Council, pers. commun., 2005). Without any pre-control monitoring, managers may underestimate the frequency of ongoing control work required to achieve the sustained population reductions necessary for Tb disease elimination.

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